

Article

Strength Model for Cement-Stabilized Marine Clay: SEM Image Analysis and Microstructural Insights

Liyang Xu ^{1,2,3}, Xipeng Wang ^{1,*}, Yanzhi Qi ¹, Chang Yuan ⁴, Zhi Ding ¹ and Riqing Xu ²¹ Department of Civil Engineering, Hangzhou City University, Hangzhou 310015, China² Research Center of Coastal and Urban Geotechnical Engineering, Zhejiang University, Hangzhou 310058, China³ Engineering Research Center for Geological Environment and Underground Space of Jiangxi Province, East China University of Technology, Nanchang 330013, China⁴ School of Civil & Architecture Engineering of ECUT, East China University of Technology, Nanchang 330013, China

* Correspondence: xpwang@hzcw.edu.cn

Abstract: This study investigates the strength development of cement-stabilized marine clay, which is influenced by a complex interplay of microstructural factors. To optimize its performance for coastal and offshore engineering, we explored the relationship between microstructure and unconfined compressive strength (UCS). Using Scanning Electron Microscopy (SEM) and the Pore/Crack Analysis System (PCAS), we analyzed samples with varying cement contents (10%, 15%, and 20%) and curing times (3, 7, 14, and 28 days). Key microstructural parameters, including porosity, particle shape, size, and arrangement, were quantified and correlated with UCS results. A novel comprehensive micro-parameter was introduced to encapsulate the combined effects of these factors, revealing an exponential relationship with strength development. The findings provide a quantitative framework for predicting the performance of cement-stabilized marine clay, contributing to more efficient solutions in geotechnical engineering.

Keywords: cement-stabilized marine clay; microstructure analysis; strength model; scanning electron microscopy



Academic Editor: Anabela Oliveira

Received: 6 January 2025

Revised: 30 January 2025

Accepted: 5 February 2025

Published: 19 February 2025

Citation: Xu, L.; Wang, X.; Qi, Y.; Yuan, C.; Ding, Z.; Xu, R. Strength Model for Cement-Stabilized Marine Clay: SEM Image Analysis and Microstructural Insights. *J. Mar. Sci. Eng.* **2025**, *13*, 388. <https://doi.org/10.3390/jmse13020388>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

In coastal and offshore areas, marine clay often presents significant geotechnical challenges due to its insufficient strength, high water content, excessive settlement, and high compressibility, rendering it unsuitable for engineering purposes [1–3]. To address these challenges and meet construction demands, various stabilizing additives have been employed. Among them, effective stabilizers include cement [4], bioencapsulation [5], nanometer magnesium oxide [6], polyurethane [7], halloysite nanotubes [8], and calcium-based additives [9]. In addition, ecofriendly options such as recycled blended tiles [10], industrial by-products [11], and granite waste [12] have also shown promise. Previous studies have confirmed the effectiveness of these stabilizers in improving the mechanical properties of marine clays.

Of these, cement stabilization remains one of the most reliable solutions for meeting diverse engineering requirements over the long term [4,13]. Several studies have highlighted the importance of understanding the cementation process and the development of strength in marine clay over time, emphasizing the role of microstructural changes such as particle bonding and void reduction during hydration [14,15]. Furthermore, the durability

of cement-stabilized marine clay under various environmental conditions, including cyclic wetting and drying, freeze–thaw cycles, and exposure to marine water, has been extensively examined [16–18].

The strength of cement-stabilized marine clay is a critical parameter for structural design and performance evaluation of marine facilities. Macro-scale clay strength is inherently governed by microstructural characteristics [19,20], making an understanding of the micro-mechanisms underlying strength evolution essential for material optimization. Cement hydration is pivotal in enhancing clay strength [21–23], with factors such as the clay-and-water-to-cement ratio, curing time, and cement content being extensively studied [24–26]. While these studies have made significant progress in understanding the general trends in strength improvement, there remains a critical gap in linking the detailed clay microstructure to its macroscopic strength development [27]. Although numerous studies have investigated the relationship between macroscopic strength and microstructural features, there is still a lack of a unified approach to quantitatively assess the impact of specific microstructural features, such as particle size distribution, porosity, and particle shape, on strength.

Recent advancements in microscopy techniques have enabled more detailed observation of soil microstructure during hydration [28]. Hydration products bond soil particles and reduce void spaces, thereby enhancing strength [29,30]. However, despite these technological advancements, most studies remain qualitative, lacking a systematic, quantitative analysis of how specific microstructural features contribute to strength. Specifically, the relationship between the size, shape, and arrangement of particles and the unconfined compressive strength (UCS) of cement-stabilized marine clay has not been fully established. Addressing this issue is vital for bridging the gap between clay microstructure and macro-scale strength, enabling precise predictions and optimizations of strength.

This study addresses this gap by developing a strength model for cement-stabilized marine clay based on quantitative analysis of its microstructure using SEM images. Cement-stabilized marine clay samples from the Taizhou coastal industrial zone were subjected to UCS testing and SEM imaging. Key microstructural parameters, including porosity, particle shape, size distribution, and arrangement, were quantified using the PCAS. The Gray Relation Analysis (GRA) method was adopted to assess the relative importance of these micro-parameters. By evaluating key microstructural features and correlating these with UCS, this research establishes a comprehensive framework for understanding the relationship between microstructure and strength, offering new insights into the micro-mechanisms governing the strength of cement-stabilized marine clay. The findings contribute to the optimization of material performance for coastal and offshore engineering applications, aligning with sustainable development goals and addressing marine geotechnical challenges.

2. Materials and Methods

2.1. Materials

The marine clay used in this study was collected from tidal flat mud in the Taizhou Coastal Industrial Zone, located in the eastern part of Zhejiang Province, China. This region is characterized by high moisture content, significant compressibility, low strength, poor permeability, and a plastic state, making it a typical example of marine clay that poses challenges for construction in coastal areas. The samples were collected in accordance with standard geotechnical procedures for soil extraction in marine environments. The basic physical properties of the marine clay, including its water content, porosity, et al. are described in Table 1. According to the Unified Soil Classification System (USCS), the soil is classified as high-plasticity clay (CH).

Table 1. Physical properties of Taizhou clay.

Water Content, ω (%)	Unit Weight, γ (kN·m ⁻³)	Specific Gravity, d_s	Porosity, n	Liquid Limit, ω_L	Plastic Limit, ω_P
59.8%	17.3	2.817	0.616	51.9	24.5

Meanwhile, the ordinary portland cement (OPC) with a strength level of 42.5 MPa (i.e., 42.5 N) from the Qianjiang cement factory was used for the cement stabilization of the clay. The cement clinker contains tricalcium silicate, dicalcium silicate, and tricalcium aluminate, which undergo chemical reactions with water to form cementitious substances. These substances bind the loose soil particles together, thereby enhancing the marine clay strength.

2.2. Sample Preparation

2.2.1. Sample Preparation for UCS Test

To prepare the Cement-Stabilized Marine Clay sample, the original marine clay was first dried in an oven at 105 °C for 24 h to remove any excess moisture and then ground to pass through a 2 mm sieve to obtain a fine powder. The dried clay powder was then mixed with 42.5 ordinary portland cement (OPC) and water. The water-to-cement ratio was maintained at 1:1, with the water content of the mixture set to 40% by weight of the dry soil. The amount of water was carefully calculated based on the dry weight of the soil to ensure consistency in the sample preparation.

The clay–cement–water mixture was thoroughly mixed using a mechanical mixer to ensure uniform distribution of the water and cement throughout the clay particles. The resulting mixture was then compacted into a standard mold (height 80 mm, diameter 39.1 mm). The sample was compacted in three layers using the standard compaction method. After compaction, the sample was left under natural conditions for 24 h to allow initial setting. Subsequently, the sample was carefully removed from the mold and immediately wrapped in plastic film to prevent moisture loss. The wrapped sample was then stored in a humidity chamber at a constant temperature of 20 ± 5 °C to maintain stable curing conditions until the planned curing time was reached, as shown in Figure 1a. The cement content and curing age of the samples are provided in Table 2.

Table 2. Cement content and curing age of the cemented clay.

No.	Original Clay	Water Content	Cement Content	Curing Age (Days)
1	Taizhou clay	40	10	28
2	Taizhou clay	40	15	28
3	Taizhou clay	40	20	28
4	Taizhou clay	40	10	14
5	Taizhou clay	40	15	14
6	Taizhou clay	40	20	14
7	Taizhou clay	40	15	7
8	Taizhou clay	40	10	3
9	Taizhou clay	40	15	3
10	Taizhou clay	40	20	3



(a)



(b)

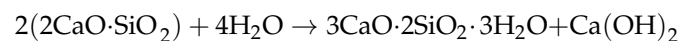
Figure 1. Sample preparation. (a) Sample for UCS test. (b) Sample for SEM imaging.

2.2.2. Sample Preparation for SEM Imaging

To obtain undisturbed surfaces for Scanning Electron Microscopy (SEM) analysis, the untreated cement-treated marine clay sample was milled, dried, and gold-coated [31]. Initially, the sample was cut into a strip measuring 2.0 cm (length) $\times$ 1.5 cm (width) $\times$ 1.5 mm (height) from the center, and two parallel grooves of 0.5 mm depth were carved along the middle, with a distance of 0.5 mm between the grooves [32]. The clay strip was then dried using a “liquid nitrogen vacuum drying method” before being fractured along the grooves to expose the undisturbed surfaces. Finally, the surface of the clay was coated with a layer of gold to make it conductive, using the SBC-12 ion sputtering machine from KYKY company [33]. Figure 1b shows the completed sample ready for SEM imaging.

2.3. Experimental Program

When cement paste is added to the clay, a reaction occurs between the cement and water. The chemical reactions can be expressed as follows:



During the cement hydration process, the $3\text{CaO}\cdot\text{SiO}_2$ (i.e., C_3S) and $2\text{CaO}\cdot\text{SiO}_2$ (i.e., C_2S) in cement can react with H_2O , generating calcium-silicate-hydrate ($3\text{CaO}\cdot 2\text{SiO}_2\cdot 3\text{H}_2\text{O}$, abbreviated as CSH) and calcium-hydroxide crystals ($\text{Ca}(\text{OH})_2$, abbreviated as CH), which alter the microstructure of the cement-treated soil. To further understand the mechanism of strength development at the micro-scale, the cemented clay sample was observed using SEM. In summary, the testing procedure included unconfined compressive strength (UCS) tests and SEM analyses. The sample preparation and testing procedures followed the Chinese standard for geotechnical testing [34].

The UCS was measured using a WDW-T50 type microcomputer-controlled electronic universal testing machine, manufactured by Jinan Testing Machine Factory in Shandong, China. A vertical displacement was applied at a rate of 1 mm/min, and the stress and strain data were collected by a microcomputer. After the stress reaches the peak value, apply 3% to 5% additional axial strain before stopping the loading. The peak axial stress is taken as the unconfined compressive strength (UCS) of the tested specimen. If the stress–strain curve of the specimen does not exhibit a peak, the test should continue until the axial strain reaches 20%, and the corresponding axial stress is considered the UCS. After the test, the upper loading plate was raised and the specimen was removed. The UCS values of the samples in Table 2 were all measured.

2.4. SEM Image

A scanning electron microscope of the FEG650 type produced by FEI Company in the Netherlands was used for SEM observation (see Figure 2). The goal was to obtain high-quality images. The accelerating voltage was 5 kV, the working distance was 10 mm, and the secondary electron imaging mode was operated. All the tests were conducted by the same experimenter, which can reduce subjectivity. For example, all the images can have similar brightness and contrast. Finally, the SEM images of all samples in Table 2 were obtained. Based on these SEM images, image processing could be conducted.



Figure 2. Scanning electron microscope of the FEG650 type.

2.5. Image Processing

The SEM image is a gray photograph of clay, whose relatively dark region represents pore space, and the relatively lighter region is referred to as clay particles. The thresholding of the image is carried out to separate the two parts. The threshold determination method has been given in our previous research [35].

Based on these threshold values, the SEM image was converted into a binarized image, and then the measurement of micro-parameters can be performed with the help of the PCAS software [36–38]. Finally, the micro-parameters can be obtained from the SEM images.

3. Results

3.1. Qualitative Analysis of SEM Image

Figure 3 presents a comparison of the microstructure of samples with varying curing ages. Specifically, Figure 3a illustrates the No. 9 sample (3 days, 15% cement), and Figure 3b shows the No. 2 sample (28 days, 15% cement).

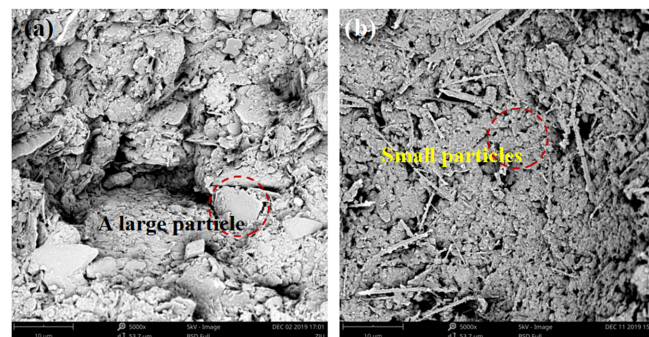


Figure 3. SEM images of cement-treated soil with different curing ages (the magnification rate is 5000 times). (a) Three days curing time, 15% cement content. (b) Twenty eight days curing time, 15% cement content.

A greater presence of needle-like and networked structures is evident in Figure 3b compared to Figure 3a. These structures represent ettringite (AFt) and calcium silicate hydrate (CSH), which serves to bond smaller particles together. This morphological feature indicates that more CSH is generated as the curing time increases. Consequently, the particle arrangement in the microstructure changes over time. Additionally, Figure 3b contains more smaller particles than Figure 3a. This is attributed to the higher formation of calcium hydroxide (CH) inside the pore spaces and solid matrix as curing progresses. As a result, there is an increase in both the variety of particle shapes and sizes. Moreover, since there is consumption and formation of materials within the sample, the porosity will also be affected. In conclusion, the micro-mechanism underlying the evolution of cement-stabilized marine clay strength involves the modification of particle arrangement, shape, size, and porosity in the microstructure.

3.2. Quantitative Analysis of SEM Image

For a deeper quantitative analysis of the micro-mechanism of strength, the conceptual model should be described using relevant micro-parameters. These micro-parameters can be derived through image processing techniques. Based on the definitions (Sections 3.2.1–3.2.4) of the various micro-parameters, four key micro-parameters—image porosity n_s , mean shape factor F , particle grading entropy G_e , and directional probability entropy H_m —were selected to represent the pore ratio, particle shape, particle size distribution, and particle arrangement in the cement-stabilized marine clay, respectively.

3.2.1. Image Porosity

In the SEM image, the total area can be divided into two components: particles and pores. The image porosity n_s is defined as the ratio of the pore area A_1 to the total area A_0 of the image [39]. Therefore, this value can be used to represent the natural porosity of the cement-stabilized marine clay.

$$n_s = \frac{A_1}{A_0} \quad (1)$$

The image porosity n_s lies within the range $[0, 1]$. When the image porosity is 0, the clay is composed entirely of particles with no pores, while when the image porosity is 1, the clay consists entirely of pores with no particles.

3.2.2. Mean Shape Factor

The mean shape factor F is used to characterize the shape of the particles in the cement-stabilized marine clay [40]. Its value range is $(0, 1]$. As the mean shape factor approaches 1, the particle shape is increasingly circular. The mean shape factor is defined as follows:

$$F = \frac{1}{m} \sum_{i=1}^m \left(\frac{P}{S} \right) \quad (2)$$

$$F_i = \frac{P}{S} \quad (3)$$

where

m is the total number of particles;

F_i is the shape factor of the i -th particle.

P is the perimeter of a circle that has the same area as the particle;

S is the actual perimeter of the particle.

3.2.3. Particle Grading Entropy

Particle grading entropy G_e is used to describe the distribution of particle sizes in the cement-stabilized marine clay [41]. The value of particle grading entropy ranges from $(0, 1]$. As the entropy increases, the particle size distribution becomes more heterogeneous. The grading entropy is defined as:

$$G_e = -\sum_{i=1}^l G_i(d) \log_i G_i(d) \quad (4)$$

where

d is the normalized diameter of particle, ranging from $(0, 1]$. $d = \frac{d_i}{d_{max}}$, d_i is the diameter of the i -th particle, while d_{max} is the largest diameter in the entire range.

l is the total number of equally divided intervals across the particle diameter range. In this study, it is set $l = 20$;

$G_i(d)$ is the proportion of particles whose normalized diameter d falls within a specified range, such as $[0, 0.1)$.

3.2.4. Directional Probability Entropy

The directional probability entropy H_m describes the spatial arrangement of particles in terms of their orientation [42]. This parameter can be used to assess the degree of orderliness in the particle arrangement within the cement-stabilized marine clay. Directional probability entropy falls within the range [0, 1]. When the value of H_m is 0, all the particles are aligned in the same direction, while a value of 1 indicates that the particles are oriented randomly. As the value of the entropy H_m increases, the particle orientations become more disordered. The directional entropy is defined as:

$$H_m = -\sum_{i=1}^k P_i(\alpha_p) \log_k P_i(\alpha_p) \quad (5)$$

where

α_p is the direction of the p -th particle, which ranges from $[0-180^\circ]$;

k is the number of equally divided areas in the whole particle direction range $[0-180^\circ]$. In this paper, it is set $k = 18$;

$P_i(\alpha)$ represents the percentage of particles whose directions α belong to a particular angular range, such as $[0^\circ, 10^\circ)$.

3.3. Results of UCS and Micro-Parameters

The measured UCS and micro-parameters of the cement-stabilized marine clay are all provided in Table 3. The UCS values ranged from 10.21 kPa to 354.2 kPa, influenced by varying curing durations and cement contents. As the curing time increased, the UCS showed consistent improvement. Similarly, higher cement content led to higher strength. This can be attributed to the hydration reactions of C_3S , C_2S , and water upon mixing cement with clay, which form C-S-H gel and CH. These products enhance the cementation between clay particles or aggregates. However, the hydration rate is influenced by the cement content. For 10% and 15% cement contents, the hydration reaction proceeds slowly during the first 14 days, leading to gradual strength gain. After 14 days, as the cement particles continue to dissolve, the reaction accelerates, resulting in a significant strength increase by 28 days. At 20% cement content, the hydration reaction is faster, leading to a more rapid increase in strength.

Table 3. Micro-parameters of untested cement-stabilized marine clay sample.

No.	Cement Slurry Content (%)	Curing Age (Days)	Porosity Before Test, n	UCS (kPa)	Micro-Parameter Value			
					n_s	G_e	H_m	F
1	10	28	0.553694	50.6	0.3616	0.3331	0.9902	0.4348
2	15	28	0.557531	158.26	0.4008	0.3384	0.9938	0.4298
3	20	28	0.560991	354.2	0.3738	0.3181	0.9946	0.4400
4	10	14	0.564174	12.05	0.3217	0.2993	0.9914	0.4305
5	15	14	0.567300	24.75	0.3994	0.3792	0.9897	0.4100
6	20	14	0.572877	122	0.4576	0.2982	0.9879	0.3981
7	15	7	0.528829	11.33	0.32568	0.2397	0.9913	0.4430
8	10	3	0.545032	11.31	0.3298	0.2436	0.9898	0.4236
9	15	3	0.552927	10.21	0.3299	0.3056	0.9884	0.4242
10	20	3	0.553694	11.2	0.3030	0.2214	0.9899	0.4318

Additionally, variations in water content and mixing uniformity may have affected the results [43,44]. For samples with a curing time of 3 days (samples No. 8, 9, and 10), the 10% cement content sample (No. 8) exhibited the highest strength of 11.31 kPa, indicating sufficient hydration and strong cement-soil bonding. In contrast, the 15% cement content sample (No. 9) showed a decrease in strength to 10.21 kPa, likely due to insufficient hydration water and uneven mixing. The 20% cement content sample (No. 10) exhibited a slight recovery in strength to 11.2 kPa, suggesting that the higher cement content compensated

for incomplete hydration by facilitating the formation of more cementitious structures. Extending the curing time to 7 days improved the strength of the 15% cement sample to 11.33 kPa, indicating further hydration and the formation of additional C-S-H gel, which enhanced particle bonding.

In addition, Figure 4 illustrates how the micro-parameters evolve as curing time increases for samples with 15% cement content. The particle grading entropy G_e exhibits a more noticeable variation during the hydration process due to the generation of smaller particles as cement hydration progresses. Both the image porosity n_s and the mean shape factor F show only slight changes as the curing age increases. The directional probability entropy H_m remains relatively stable during curing. Figure 5 demonstrates how the micro-parameters evolve with varying cement content for samples cured for 14 days. The cement content has a more significant effect on the image porosity n_s and particle grading entropy G_e than on the mean shape factor F and directional probability entropy H_m . To further explore the relationship between each micro-parameter and UCS, Gray Relation Analysis (GRA) was conducted.

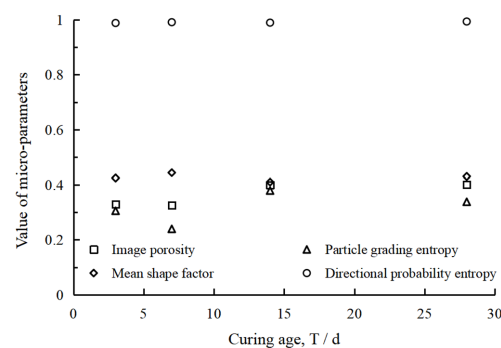


Figure 4. The evolution of micro-parameters with increasing curing age.

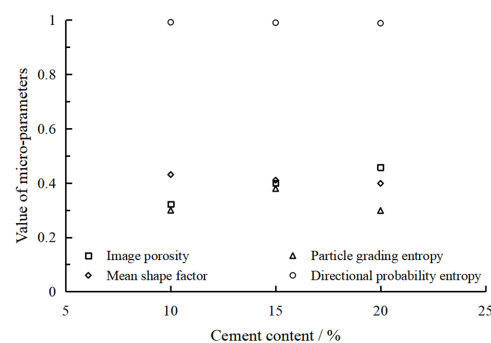


Figure 5. The evolution of micro-parameters with increasing cement content.

4. Discussion

4.1. Gray Relation Analysis of Micro-Parameter Influences

Gray Relation Analysis (GRA) is a multi-factor statistical method used to study the relationships between various influencing factors [45,46]. In this study, the strength of cement-stabilized marine clay and its influencing factors are considered within a gray system. The influence of these factors can be quantitatively assessed using the gray relational grade γ_{0i} obtained from the GRA. It is important to note that a higher gray relational grade γ_{0i} indicates a stronger influence of the corresponding micro-parameter on the UCS.

The GRA results show the following relational grades γ_{0i} for the micro-parameters: image porosity (0.7586), mean shape factor (0.7446), directional probability entropy (0.7436), and particle grading entropy (0.7628). Among these, particle grading entropy has the highest relational grade, followed by image porosity, which is slightly lower than particle

grading entropy but higher than the other two micro-parameters—mean shape factor and directional probability entropy. The relational grades of the mean shape factor and directional probability entropy are nearly equal. These results suggest that the order of importance for the micro-parameters influencing strength is as follows: $G_e > n_s > F \cong H_m$.

4.2. Comprehensive Micro-Parameter and Clay Strength

To account for the combined influence of porosity, particle arrangement, size, and shape during the hydration process, a comprehensive micro-parameter is M introduced. This parameter is a combination of the four micro-parameters mentioned above, defined as follows:

$$M = \frac{\left(\frac{n_s}{c \times \lg(t)} \right) \times F}{H_m G_e} \quad (6)$$

where c is the cement content, expressed as a decimal (e.g., 10% as 0.10); t is the curing age (unit: day).

The strength of cement-stabilized marine clay increases with curing time, as the microstructure undergoes modifications. The relationship between strength and the comprehensive micro-parameter for these clay samples is shown in Figure 6a. Similarly, as cement content increases, the strength also improves due to changes in the microstructure. And the relationship between their strength and the corresponding comprehensive micro-parameter is presented in Figure 6b. These results indicate that the functional form of the relationship is similar for both different curing times and cement contents. Therefore, both conditions can be fitted using a unified exponential function, as shown in Figure 6c.

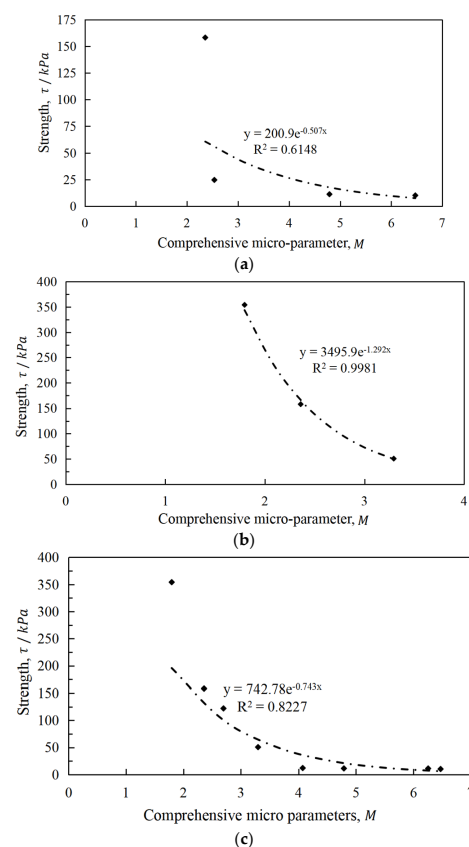


Figure 6. Strength model for the cement-stabilized marine clay. (a) Relation between M and UCS influenced by curing age. (b) Relation between comprehensive micro-parameter M and UCS influenced by cement content. (c) Unified exponential function of all comprehensive micro-parameters M and UCS.

Based on the experimental results in this paper, the relationship between comprehensive micro-parameter and UCS of cement-stabilized marine clay can be obtained by the exponential function fitting:

$$\tau = ae^{-bM} \quad (7)$$

where τ is the UCS of cement-stabilized marine clay, M is the comprehensive micro-parameter, a , b are the coefficients in the equation. The values of a , b for cement-stabilized marine clay are shown in Figure 6.

5. Conclusions

This study investigates the strength model of cement-stabilized marine clay. The following conclusions are drawn:

The strength improvement in cement-stabilized marine clay is attributed to the microstructural changes induced by cement hydration. These changes can be effectively described using micro-parameters such as porosity (n_s), particle shape (F), size (G_e), and arrangement (H_m), which play key roles in influencing strength development.

The sensitivity analysis conducted using Gray Relation Analysis (GRA) reveals the relative importance of these microstructural parameters. Among them, particle grading entropy G_e is identified as the most influential factor, followed by image porosity n_s , with the mean shape factor F , and directional probability entropy H_m showing a similar degree of influence. These findings provide a clear pathway for optimizing cement-stabilized marine clay by enhancing key microstructural features.

A comprehensive micro-parameter, which combines the effects of porosity, particle shape, size, and arrangement, has been proposed. This parameter is shown to have an exponential relationship with the unconfined compressive strength (UCS), providing a robust framework for strength prediction. However, further validation through extensive testing is recommended to refine the model and confirm its applicability in broader scenarios.

This research provides valuable insights for optimizing the strength of cement-stabilized marine clay in coastal and offshore engineering applications. By understanding the microstructural mechanisms that govern strength development, engineers can make more informed decisions when designing and constructing marine infrastructure, particularly in challenging coastal environments where clay conditions are variable and dynamic.

Practical Applications: This study contributes significantly to the optimization of cement-stabilized marine clay for marine engineering, offering important strategies for improving soil strength and stability. The findings can guide the design of coastal and offshore infrastructure, especially in areas where soil modification and stabilization are critical for maintaining the performance and safety of structures. Furthermore, this study lays a foundation for future research on the relationship between other macroscopic properties of marine clay and its microstructural parameters. Future work will expand the analysis to include additional macromechanical parameters, such as compressive modulus, and conduct a more systematic study incorporating these microstructural parameters.

Author Contributions: Conceptualization, Z.D. and R.X.; methodology, L.X.; investigation, Y.Q.; resources, X.W.; data curation, L.X.; writing—original draft preparation, L.X.; writing—review and editing, X.W.; visualization, C.Y.; supervision, R.X.; funding acquisition, Z.D. and C.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Key Research and Development Program of Zhejiang, grant number 2023C03182; National Natural Science Foundation of China, grant number 52178400 and 52278418; Key Project of Zhejiang Provincial Natural Science Foundation, grant number LHZ20E080001; Zhejiang Provincial Key Research and Development Project, grant number 2020C01102; Open Fund from Engineering Research Center for Geological Environment and Under-

ground Space of Jiangxi Province, grant number JXDHJJ2024-004; The Opening Fund of State Key Laboratory of Frozen Soil Engineering (grant number: SKLFSE202012); The National Natural Science Foundations of China (grant number: 42107203); The Natural Science Foundation Projects of Jiangxi Province (grant number: 20232BAB214077, 20242BAB25305); Underground Engineering Risk Digital Control Research Center of Jiangxi Province (grant number: JXDFJJ2024-007).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Yim, W.W.S. Offshore Quaternary sediments and their engineering significance in Hong Kong. *Eng. Geol.* **1994**, *37*, 31–50. [\[CrossRef\]](#)
2. Zainuddin, N.; Yunus, N.Z.M.; Al-Bared, M.A.M.; Marto, A.; Harahap, I.S.H.; Rashid, A.S.A. Measuring the engineering properties of marine clay treated with disposed granite waste. *Measurement* **2019**, *131*, 50–60. [\[CrossRef\]](#)
3. Wu, P. Physical and Numerical Modelling Study of Hong Kong Marine Deposits Improved by Reinforcements and Vertical Drains. Ph.D. Thesis, Hong Kong Polytechnic University, Hong Kong, 2021.
4. Al-Bared, M.M.; Marto, A. A review on the geotechnical and engineering characteristics of marine clay and the modern methods of improvements. *Malays. J. Fundam. Appl. Sci.* **2017**, *13*, 825–831. [\[CrossRef\]](#)
5. Rojas-Sánchez, B.; Guzmán-Guzmán, P.; Morales-Cedeño, L.R.; Orozco-Mosqueda, M.D.C.; Saucedo-Martínez, B.C.; Sánchez-Yáñez, J.M.; Fadji, A.E.; Babalola, O.O.; Glick, B.R.; Santoyo, G. Bioencapsulation of microbial inoculants: Mechanisms, formulation types and application techniques. *Appl. Biosci.* **2022**, *1*, 198–220. [\[CrossRef\]](#)
6. Gou, J.; Zhuge, J. Nanotechnology safety in the marine industry. In *Nanotechnology Safety*; Asmatulu, R., Ed.; Elsevier: Amsterdam, The Netherlands, 2013; pp. 161–174.
7. Saleh, S.; Yunus, N.Z.M.; Ahmad, K.; Ali, N. Stabilization of marine clay soil using polyurethane. In *MATEC Web of Conferences. EDP Sciences*; EDP Science: Ulis, France, 2018; Volume 250, p. 01004.
8. Emmanuel, E.; Yong, L.L.; Anggraini, V.; Pasbakhsh, P. Can halloysite nanotubes be used to remediate zinc and lead-contaminated marine clay? A solidification/stabilization approach. *Appl. Clay Sci.* **2020**, *186*, 105441. [\[CrossRef\]](#)
9. Latifi, N.; Meehan, C.L.; Abd Majid, M.Z.; Horpibulsuk, S. Strengthening montmorillonitic and kaolinitic clays using a calcium-based non-traditional additive: A micro-level study. *Appl. Clay Sci.* **2016**, *132*, 182–193. [\[CrossRef\]](#)
10. Ly, H.B.; Nguyen, T.A. Enhancing compressive strength and sustainability: A machine learning approach to recycled brick and tile concrete mix design. *Mater. Today Commun.* **2024**, *40*, 109642. [\[CrossRef\]](#)
11. Sakir, S.; Raman, S.N.; Safiuddin, M.; Kaish, A.A.; Mutalib, A.A. Utilization of by-products and wastes as supplementary cementitious materials in structural mortar for sustainable construction. *Sustainability* **2020**, *12*, 3888. [\[CrossRef\]](#)
12. Moura, H.R.D.C.V.; Pedroti, L.G.; Lopes, M.M.S.; De Carvalho, J.M.F.; Ribeiro, J.C.L.; Dias, J.C.B. Influence of biocide and dispersant additives on the performance and durability of building paints produced with granite waste. *Constr. Build. Mater.* **2023**, *409*, 134112. [\[CrossRef\]](#)
13. Xiao, H.; Shen, W.; Lee, F.H. Engineering Properties of Marine Clay Admixed with Portland Cement and Blended Cement with Siliceous Fly Ash. *J. Mater. Civ. Eng.* **2017**, *29*, 04017177. [\[CrossRef\]](#)
14. Wei, X.; Liu, H.; Ku, T. Effects of plastic fines content on the engineering properties of cement-stabilized sands. *Granul. Matter* **2021**, *23*, 1–13. [\[CrossRef\]](#)
15. Chaudhary, V.; Yadav, J.S.; Dutta, R.K. Impact of nano-silica and cement on geotechnical properties of bentonite soil. *Indian Geotech. J.* **2024**, *54*, 1420–1437. [\[CrossRef\]](#)
16. Li, N.; Zhu, Y.; Zhang, F.; Lim, S.M.; Wu, W.; Wang, W. Unconfined compressive properties of fiber-stabilized coastal cement clay subjected to Freeze–Thaw cycles. *J. Mar. Sci. Eng.* **2021**, *9*, 143. [\[CrossRef\]](#)
17. Chen, Q.; Yu, R.; Gaoliang, T.; Nimbalkar, S. Microstructure, strength and durability of nano-cemented soils under different seawater conditions: Laboratory study. *Acta Geotech.* **2023**, *18*, 1607–1627. [\[CrossRef\]](#)
18. Yu, H.; Joshi, P.; Lau, C.; Ng, K. Coal-derived char for durability improvement of cement stabilized soil under freeze–thaw, wet–dry, and sulfate attack. *Can. Geotech. J.* **2025**, *62*, 1–20. [\[CrossRef\]](#)
19. Yue, J.; Lei, Y.; Zhu, X.; Xu, S.; Yue, M. Macroscopic compressive strength study of historical grey bricks based on microscopic scale. *Constr. Build. Mater.* **2024**, *421*, 135634. [\[CrossRef\]](#)
20. Cotecchia, F.; Guglielmi, S.; Cafaro, F.; Gens, A. Micro to macro investigation of clays advising their constitutive modelling-part I. *Soils Rocks* **2024**, *47*, e2024011723. [\[CrossRef\]](#)

21. Horpibulsuk, S.; Phojan, W.; Suddeepong, A.; Chinkulkijniwat, A.; Liu, M.D. Strength development in blended cement admixed saline clay. *Appl. Clay Sci.* **2012**, *55*, 44–52. [\[CrossRef\]](#)
22. Scrivener, K.L.; Juilland, P.; Monteiro, P.J. Advances in understanding hydration of Portland cement. *Cem. Concr. Res.* **2015**, *78*, 38–56. [\[CrossRef\]](#)
23. Jahami, A.; Chamseddine, F.; Issa, C.A.; Zeaiter, H.; Salhab, A.; Khalil, F. Utilization of Nano Clay in Concrete: A Review of Mechanical, Durability, and Workability Properties. *ES Mater. Manuf.* **2024**. [\[CrossRef\]](#)
24. Ng, C.; Alengaram, U.J.; Wong, L.S. A review on microstructural study and compressive strength of geopolymer mortar, paste and concrete. *Constr. Build. Mater.* **2018**, *186*, 550–576. [\[CrossRef\]](#)
25. Bi, J.; Chian, S.C. Modelling of three-phase strength development of ordinary Portland cement-and Portland blast-furnace cement-stabilised clay. *Geotechnique* **2020**, *70*, 80–89. [\[CrossRef\]](#)
26. Xu, Z.H.; Wu, Q.C.; Zhang, R.J.; Liu, S.J.; Zheng, J.J. Strength Behavior of Slurry-Like Mud Treated with Physicochemical Combination Method. *Int. J. Geomech.* **2024**, *24*, 04024072. [\[CrossRef\]](#)
27. Horpibulsuk, S.; Rachan, R.; Suddeepong, A. Assessment of strength development in blended cement admixed Bangkok Clay. *Constr. Build. Mater.* **2011**, *25*, 1521–1531. [\[CrossRef\]](#)
28. Zhang, H.; Liu, Z.; Ma, X.; Zhang, H.; Qian, J. Monitoring of early curing stage of cemented soil using polymer optical fiber sensors and microscopic observation. *Constr. Build. Mater.* **2024**, *436*, 136888. [\[CrossRef\]](#)
29. Lei, H.Y.; Wang, L.; Jia, R.; Jiang, M.; Zhang, W.; Li, C. Effects of chemical conditions on the engineering properties and microscopic characteristics of Tianjin dredged fill. *Eng. Geol.* **2020**, *269*, 105548. [\[CrossRef\]](#)
30. Chian, S.C.; Bi, J. Influence of grain size gradation of sand impurities on strength behaviour of cement-treated clay. *Acta Geotech.* **2021**, *16*, 1127–1145. [\[CrossRef\]](#)
31. Xu, R.Q.; Xu, L.Y.; Duan, J.C.; Xu, X.; Fu, J.S.; Wu, X.B. Microstructure morphology and optimization of influencing factors in quantitative analysis of soft clay. *J. Cent. South Univ. (Sci. Technol.)* **2016**, *47*, 2723–2729. (In Chinese)
32. Xu, R.Q.; Jiang, J.Q.; Dong, M.; Xu, L.Y. Experimental study on evolution of microscopic contact area in saturated soft soil during shear process with drainage. *J. Cent. South Univ. (Sci. Technol.)* **2020**, *51*, 411–419. (In Chinese)
33. Deng, Y.W. Soft Clay Micro-Quantitative Research and Its Application. Ph.D. Thesis, Zhejiang University, Hangzhou, China, 2015. (In Chinese).
34. Ministry of Water Resources of the People's Republic of China. *GB/T 50123-2019*; Standard for Geotechnical Test Method. National Bureau of Quality and Technical Supervision, Ministry of Construction in China: Beijing, China, 2019.
35. Xu, L.Y.; Xu, R.Q.; Shashank, B.S.; Chen, X.H.; Yu, J.L.; Wu, C.Z. An Improved Quantification Method for Characterization of Clay Microstructure Using SEM. *Environ. Geotech.* **2024**, *11*, 319–338. [\[CrossRef\]](#)
36. Liu, C.; Shi, B.; Zhou, J.; Tang, C.S. Quantification and characterization of microporosity by image processing, geometric measurement and statistical methods: Application on SEM images of clay materials. *Appl. Clay Sci.* **2011**, *54*, 97–106. [\[CrossRef\]](#)
37. Liu, C.; Tang, C.S.; Shi, B.; Suo, W.B. Automatic quantification of crack patterns by image processing. *Comput. Geosci.* **2013**, *57*, 77–80. [\[CrossRef\]](#)
38. Tang, C.S.; Shi, B.; Cui, Y.J.; Liu, C.; Gu, K. Desiccation cracking behavior of polypropylene fiber-reinforced clayey soil. *Can. Geotech. J.* **2012**, *49*, 1088–1101. [\[CrossRef\]](#)
39. Lu, J.Y. Solidification Research and Microscopic Quantitative Study of Ningbo Mucky Soil. Ph.D. Thesis, Zhejiang University, Hangzhou, China, 2017. (In Chinese).
40. Wang, Q.; Sun, M.Q.; Sun, T.; Sun, T. Microstructure features for dredger fill by different solidified technologies. *J. Tongji Univ. (Nat. Sci.)* **2013**, *41*, 1286–1292. (In Chinese)
41. Tian, H.; Kong, L.W.; Zhao, C. Characterization of particle breakage with grading entropy on shell sand. *Chin. J. Geotech. Eng.* **2014**, *36*, 1152–1159. (In Chinese)
42. Lei, H.Y.; Hu, Y.; Lei, S.H.; Qi, Z.Y.; Xu, Y.G. Analysis of microstructure characteristics of air-booster vacuum preloading for ultra-soft dredger fills. *Rock Soil Mech.* **2019**, *40*, 32–40. (In Chinese)
43. Wang, F.T.; Li, K.Q.; Liu, Y. Optimal water-cement ratio of cement-stabilized soil. *Constr. Build. Mater.* **2022**, *320*, 126211. [\[CrossRef\]](#)
44. Vu, T.B.; Dang, V.Q.; Ngo, Q.A.; Ho, L.S. Influence of some factors on the mechanical properties of cement-treated clay for shallow mixing in Vietnam: A comparative study. *Results Eng.* **2023**, *17*, 101011. [\[CrossRef\]](#)
45. Kuo, Y.; Yang, T.; Huang, G.W. The use of grey relational analysis in solving multiple attribute decision-making problem. *Comput. Ind. Eng.* **2008**, *55*, 80–93. [\[CrossRef\]](#)
46. Ni, X.; Li, J.; Xu, J.; Shen, Y.; Liu, X. Grey relation analysis and multiple criteria decision analysis method model for suitability evaluation of underground space development. *Eng. Geol.* **2024**, *338*, 107608. [\[CrossRef\]](#)

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.